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A robust high-speed sliding mode control of permanent magnet synchronous motor based on simplified hysteresis current comparison

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ABSTRACT

A robust high-speed sliding mode control (SMC) of three phase permanent magnet synchronous motor (PMSM) is presented. The SMC served for inner speed control while a simplified hysteresis current control (HCC) scheme was used in the outer current control to generate gating signals for the inverter switches. The present research leverages on the ability of SMC to directly access system speed error which it attempts driving to zero by cancelling modelling uncertainties and disturbances. Performance comparison was done for the SMC model and an existing model having classical PI controller. With the initial positive speed command of 200rpm at 5Nm constant loading, rotor speed with SMC neatly settled to the reference speed at 0.085 seconds without overshoot while the rotor speed of the model with PI controller settled at 0.217 seconds after overshoot. This translates to 155.3% speed enhancement. Similar superior speed performance of the SMC was also observed during recovering from sudden speed reversal. While the SMC model recovered and settled to the reference speed of -200rpm at 0.369 seconds, the model with PI controller settled at 0.482 seconds. From the results, it can be seen that SMC demonstared superiority over the conventioanl PI controller for complex drives systems.

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1. INTRODUCTION

The popularity of controlled permanent magnet synchronous motors (PMSMs) is on the increase for applications in the industry within the medium and low power ranges. They have superior characteristics such as high torque/inertia ratio, compact size, lower noise and accurate positioning [1]-[5]. PMSMs have the advantage of high efficiency when compared with the induction motor [6], high reliability, fast dynamics and very good compatibility [7]-[8]. The absence of rotor winding due to the use of the rotor magnets is responsible for the enhanced features. Complexity of PMSM makes it a nonlinear system coupled with its exposure to uncertainties such as perturbations, disturbances and load changes [9]-[14].

Several non-linear control methods have been used in the torque and speed control of PMSMs. A fuzzy adaptive internal model control (IMC) schemes, considering control input saturation, was presented in [15]. The backstepping speed observer and adaptive backstepping control were used in [16] for PMSM speed and torque control via current source inverter (CSI). The scheme showed robustness on both electromagnetic and mechanical parameters of the motor. Linear quadratic regulator (LQR) utilizing quadratic cost function for the determination of control performance was used in [17] to linearize the inherently non-linear mathematical model of the motor. Results from this control technique show that LQR exhibits better system dynamic performance with reference to transition time and speed overshoot in comparison with traditional PID controller.

Other nonlinear methods that have been used to control the PMSM includes a neural network loss minimization control [18], generalized predictive control (GPC), sliding mode controller (SMC) [19]-[20], Fuzzy logic controller (FLC) [21]. Generally, when compared to the linear control using PID controllers, nonlinear control methods, since the PMSMs are complex nonlinear systems, are more suitable in achieving better systems dynamics and steady state performance. In this work, sliding mode control (SMC) is employed for accurate speed and position sensing for PMSM drive that employs a robust HCC for inverter gating signal generation. Specifically, the present research leverages on the unique ability of the SMC to have direct access to the systems speed error which it attempts driving to zero by cancelling modelling uncertainties and disturbances. Results obtained were compared with results obtained in the model of [3], [12] where the same simplified HCC was used for outer current control but classical PI speed controller was employed for inner speed loop control of the same drives system. MATLAB/Simulink 2018 version was used for modelling and simulation in this research.

2. D-Q MODELLING OF PMSM

The rotor permanent magnets are responsible for the production of the main magnetic flux. Thus, dq-axis voltage equations, the electromagnetic torque and the system mechanical models are respectively derived as [3], [22]-[23]:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \frac{dL_q}{dt} & \omega_r L_d \\ -\omega_r L_q & R_s + \frac{dL_d}{dt} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \varphi_m \\ \frac{d\varphi_m}{dt} \end{bmatrix} \tag{1}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left[\varphi_m i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{2}$$

$$T_e = T_L + B\omega_r + \frac{Jd\omega_r}{dt} \tag{3}$$

where, $V_d,\ V_q, i_d, i_q, \omega_r, R_s, L_d, L_q,\ B, J, T_L, T_e\ and\ P$ are as defined in [7]. The constant rotor permanent magnet flux is φ_m, hence $\frac{d\varphi_m}{dt} = 0$.

3. SMC SPEED CONTROL OF PMSM

Speed error e is the difference between the commanded speed reference, ω_d, and the rotor speed feedback, ω_r, such that $e = \omega_d - \omega_r$ [24], [25].
From (3),

$$\frac{d\omega_r}{dt} = \frac{T_e}{J} - \frac{T_L}{J} - \frac{B\omega_r}{J} \tag{4}$$

from (2), for a surface PMSM,

$$\frac{d\omega_r}{dt} = \frac{3P\varphi_m i_q}{2J} - \frac{T_L}{J} - \frac{B\omega_r}{J}$$

$$\dot{\omega}_r = \frac{3P\varphi_m i_q}{2J} - \frac{T_L}{J} - \frac{B\omega_r}{J} \tag{5}$$

taking the derivative of the tracking error (e), we have (6):

$$\dot{e} = \dot{\omega}_d - \dot{\omega}_r$$
$$\dot{e} = \dot{\omega}_d - [\frac{3P\varphi_m i_q}{2J} - \frac{T_L}{J} - \frac{B\omega_r}{J}] \quad (6)$$

taking double derivative of e we have (7):

$$\ddot{e} = \ddot{\omega}_d - \ddot{\omega}_r$$
$$\ddot{e} = \ddot{\omega}_d - \frac{d}{dt}\dot{\omega}_r$$
$$\ddot{e} = \ddot{\omega}_d - \frac{d}{dt}[\frac{3P\varphi_m i_q}{2J} - \frac{T_L}{J} - \frac{B\omega_r}{J}]$$
$$\ddot{e} = \ddot{\omega}_d - [\frac{3P\varphi_m \dot{i_q}}{2J} - 0 - \frac{B\dot{\omega}_r}{J}]$$
$$\ddot{e} = \ddot{\omega}_d - [\frac{3P\varphi_m \dot{i_q}}{2J} - \frac{B\dot{\omega}_r}{J}] \quad (7)$$

defining the sliding surface, we have (8):

$$s = \dot{e} + ce \quad (8)$$

The PMSM speed system equivalent controller is calculated by setting $\dot{s} = 0$

$$\dot{s} = \ddot{e} + c\dot{e} \quad (9)$$

$$\dot{s} = \left[\ddot{w}_d - \frac{3P\varphi_m \dot{i_q}}{2J} + \frac{B\dot{\omega}_r}{J}\right] + c\dot{e} = 0 \quad (10)$$

therefore from:

$$\ddot{\omega}_d - \frac{3P\varphi_m \dot{i_q}}{2J} + \frac{B\dot{\omega}_r}{J} + c\dot{e} = 0$$
$$\frac{3P\varphi_m \dot{i_q}}{2J} = \ddot{\omega}_d + \frac{B\dot{\omega}_r}{J} + c\dot{e} \quad (11)$$

setting $\frac{3P\varphi_m}{2J} = b$

$$\therefore b\dot{i_q} = \ddot{\omega}_d + \frac{B\dot{\omega}_r}{J} + c\dot{e}$$
$$\dot{i_q} = \frac{1}{b}[\ddot{\omega}_d + \frac{B\dot{\omega}_r}{J} + c\dot{e}] \quad (12)$$

integrating (12),

$$i_q = \frac{1}{b}[\dot{\omega}_d + \frac{B\omega_r}{J} + ce]$$

the equivalent control $U_{eq} = i_q$ [26]

$$\therefore u_{eq} = \frac{1}{b}[\dot{\omega}_d + \frac{B\omega_r}{J} + ce] \quad (13)$$

the switching controller is designed as (14):

$$u_s = ksgn(s) \quad (14)$$

the parameter $k > 0$ is a controller gain
finally, the control law is a sum of of (13) and (14):

$$U = u_{eq} + u_s = \frac{1}{b}\left[\dot{\omega}_d + \frac{B\omega_r}{J} + ce\right] + ksgn(s) \quad (15)$$

Figure 1 is a block diagram of (1)

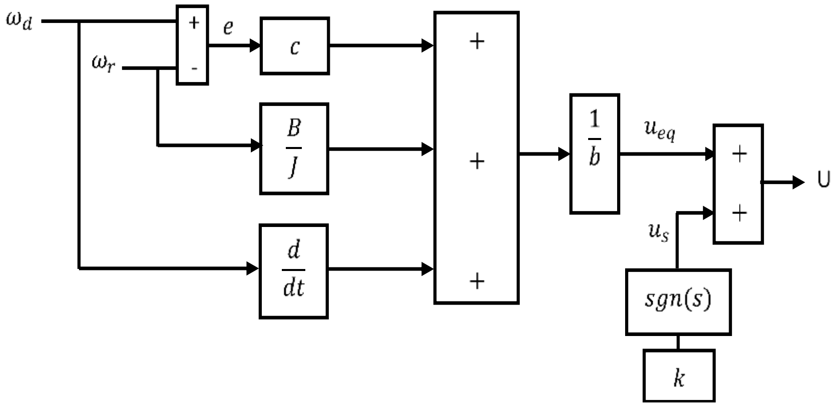

Figure 1. SMC controller block diagram

4. OVERALL CONTROL PROCEDURE

Complete system diagram is shown in Figure 2. Rotor sensed speed ω_r is processed by a 1st order low pass filter before comparison with reference speed ω_d. An error $e = \omega_d - \omega_r$ is generated which, in addition to ω_d and ω_r, serves as the input to the sliding mode control unit already described in Figure 1. The SMC unit generates a suitable control signal u , which in this case, is stator q-axis reference current (i_q^*). This drives the error, e, to zero by enabling the system speed response ω_r to attain the set reference ω_d. The i_q^*, i_d^* and θ_e are the input signals of the reference stator current estimator by inverse park's transform. The phase currents, i_a , i_b and i_c , in conjunction with corresponding generated reference currents i_a^* , i_b^* , i_c^* and Δi_q^* are compared to generate the gating signals, as illustrated in Figure 3, for the inverter with power circuit shown in Figure 4. Where Δ is a variable hysteresis window. The control logic for the gating signal generation is illustrated in [22].

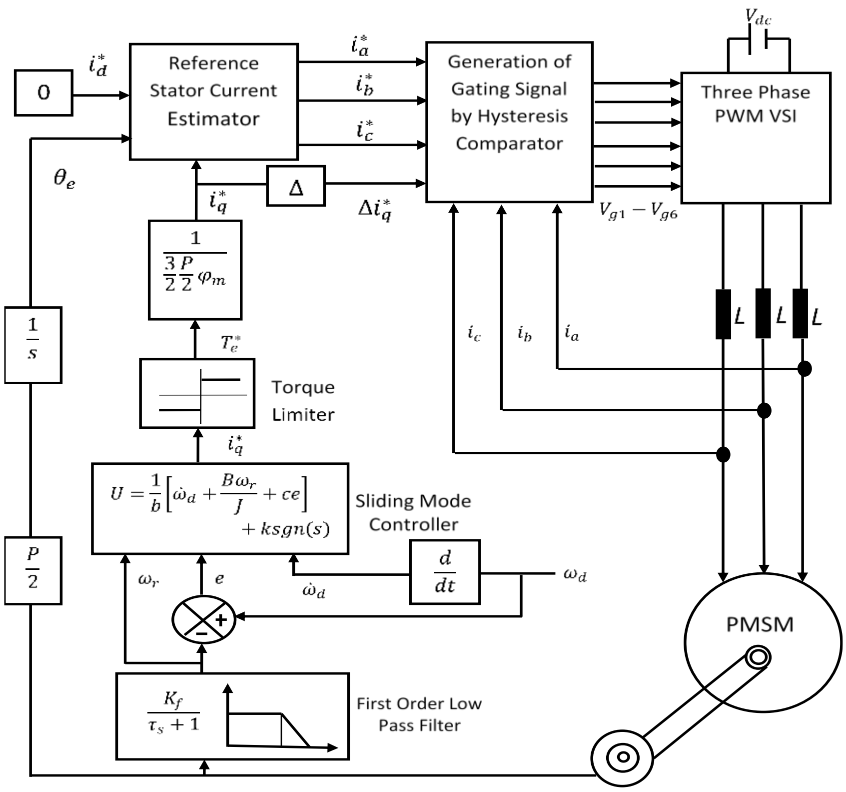

Figure 2. Complete system diagram of the PMSM drives with SMC

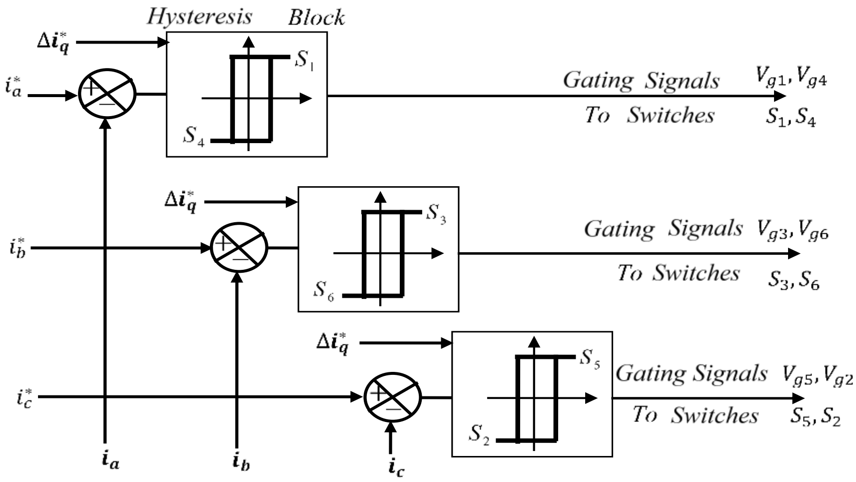

Figure 3. Generation of gating signals

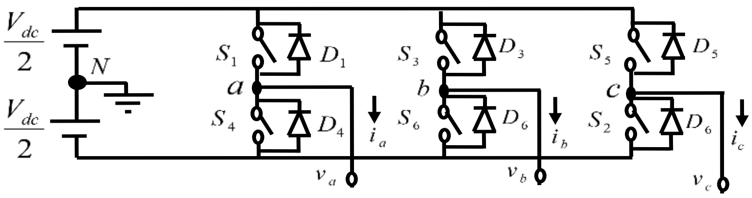

Figure 4: Three-phase inverter power circuit

5. COMPARISON OF THE RESULTS

In this section, plots of Figures 5-12 obtained from MATLAB/Simulink are used to compare the performance of this developed drives system employing SMC for inner speed control with the performance of the same system that employs classical PI controller for inner speed control as already reported in [3], [15]. In both cases, the outer current control is by HCC. PMSM parameters are shown in Table 1.

Table 1. PMSM parameters

Motor parameters	Value
Rated Power	4 Hp
Frequency	50 Hz
Stator resistance (Rs)	0.2 Ω
Constamt rotor flux linkage(λ_f)	0.175 Wb
Inductance d axis (L_d)	0.0085 H
Inductance q axis (L_q)	0.0085 H
Inertia constant (J)	0.42 Kgm^2
No. of poles (P)	6

The sensed rotor speed obtained with SMC and the PI controllers are compared with the speed reference as shown in Figure 5. With a positive speed command of 200rpm, speed response with the SMC neatly settled at the reference at 0.085 seconds without overshoot while the speed response of the PI controller experienced overshoot before settling to the speed refence at 0.217 seconds. Sudden (step) reference speed reversal from 200rpm to -200 rpm occurred at 0.25 seconds leading to change in speed orientation for the two models. At -200rpm, the SMC seamlessly traced the speed reference while the PI controller had negative overshot before settling to -200 rpm.

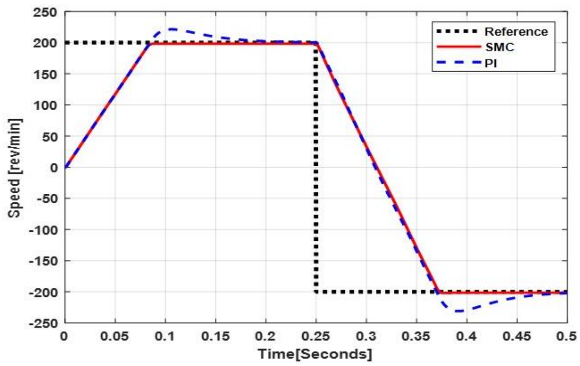

Figure 5. Reference speed, ω_d and rotor speed, ω_r

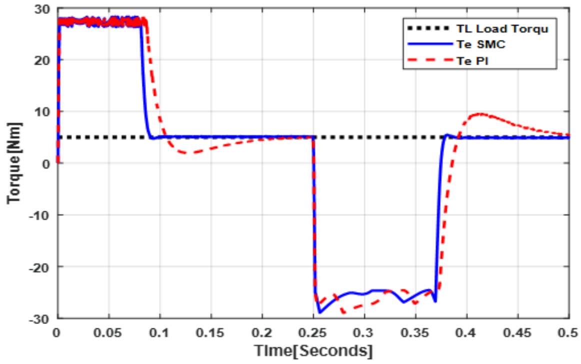

Figure 6. Electromagnetic torque, T_e and load torque, T_L

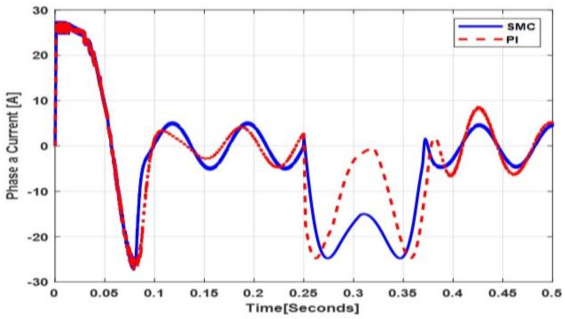

Figure 7. Stator current for Phase ‘a’

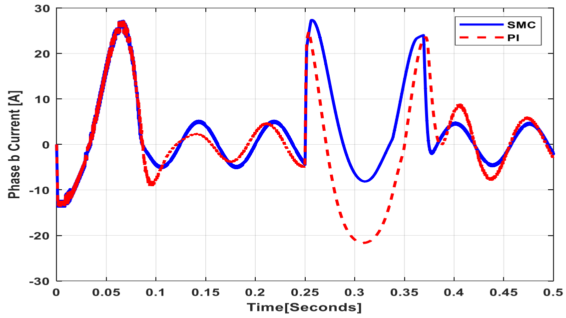

Figure 8. Stator current for Phase ‘b’

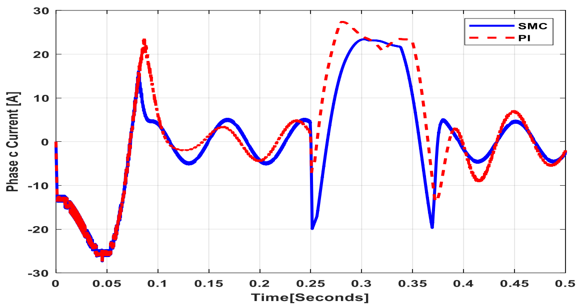

Figure 9. Stator current for Phase ‘c’

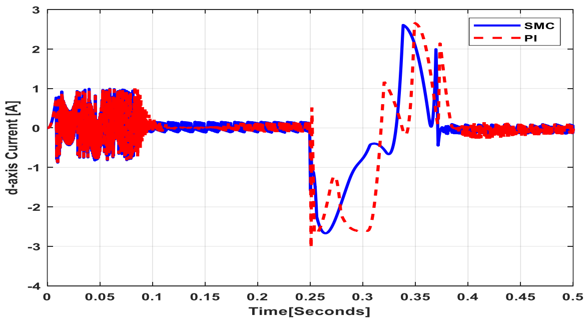

Figure 10. d axis stator current, i_d

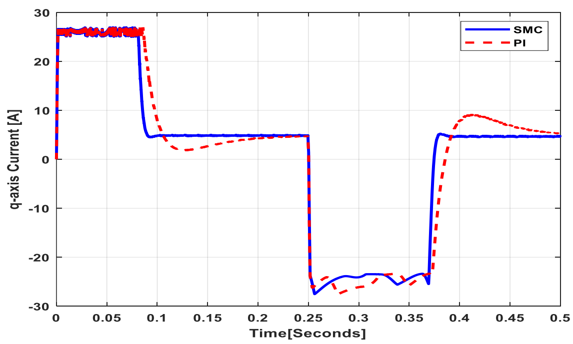

Figure 11. q axis stator current, i_q

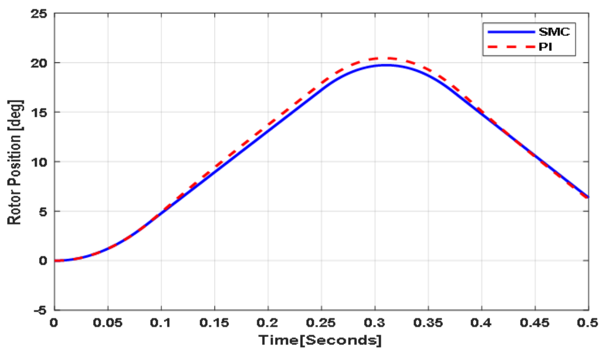

Figure 12. Rotor position, θ_r

Figure 6 shows the load torque T_L in comparison with the electromagnetic torque T_e using the SMC and PI controller. The electromagnetic torque remained constant to sustain speed build-up. At the point when rotor speed equals reference speed, electromagnetic torque reduces to the load torque value of 5Nm with the model with SMC settling at the load torque faster since there is no speed overshot. Torque recovery due to speed reversal takes the same form with the model with SMC showing better dynamic behavior as shown.

The three phase currents for the model with SMC and PI are respectively compared for phases a, b, and c in Figures 7, 8 and 9. Better dynamic performances are obtained for the model with SMC in each case. The models being field orientation controlled (FOC), the stator d-axis currents, shown in Figure 10, for the SMC and the PI models averages to zero to track the reference value which is zero in FOC. Current transients due to speed reversal are also seen.

The stator q-axis current, shown in Figure 11, is in direct proportion to electromagnetic torque T_e because being the torque controlling component of the stator current. Faster dynamic behaviour was observed for SMC model. The rotor position for the two models are compared in Figure 12. Since the model with SMC attained steady state much faster than the model with PI controller, it is observed that the rotor position for the SMC, is at every time instant, ahead of the rotor position for the PI controller.

6. CONCLUSION

This research has leveraged on the unique ability of the SMC to have direct access to the systems speed error which it attempts driving to zero thereby cancelling modelling uncertainties and disturbances. SMC was employed for inner speed control of the motor while a simplified HCC was used for the outer current control. This is so because of the proportionality of torque and current in both stationary and rotor frames of reference whereby effective current control results in effective torque and speed control.

Responses from the developed SMC model were compared with responses from an earlier model that utilizes classical PI controller for inner speed control employed on the same PMSM under the same condition of step speed command from 200rpm to -200rpm and constant load torque of 5Nm.

With the initial positive speed command of 200rpm at 5Nm loading, speed response with the SMC neatly settled at the reference at 0.085 seconds without overshoot while the speed response of the PI controller experienced overshoot before settling to the speed refence at 0.217 seconds. This translates to 155.3% speed enhancement. The same superior speed performance of the SMC is observed during recovering from sudden speed reversal at 0.25 seconds.

This research has provided sufficient evidence that the SMC exhibits more robust performance and faster response time than the PI controller in the control of complex drives systems under the same condition. MATLAB/Simulink 2018 version played a vital role in this research by presenting a suitable environment for modeling and simulation.

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